Simulation of atmospheric temperature effects on cosmic ray muon flux

S. C. TOGNINI[1], R. A. GOMES[1]
[1]Instituto de Física, Universidade Federal de Goiás
stognini@fnal.gov / stognini@posgrad.ufg.br

MINOS

The collision between a cosmic ray and an atmosphere nucleus produces a set of secondary particles, which will decay or interact with other atmosphere elements. This set of events produced a primary particle is known as an extensive air shower (EAS) and is composed by a muonic, a hadronic and an electromagnetic component. The muonic flux, produced mainly by pions and kaons decays, has a dependency with the atmosphere's effective temperature: an increase in the effective temperature results in a lower density profile, which decreases the probability of pions and kaons to interact with the atmosphere and, consequently, resulting in a major number of meson decays. Such correlation between the muon flux and the atmosphere's effective temperature was measured by a set of experiments, such as AMANDA, Borexino, MACRO and MINOS. This phenomena can be investigated by simulating the final muon flux produced by two different parameterizations of the isothermal atmospheric model in CORSIKA, where each parameterization is described by a depth function which can be related to the muon flux in the same way that the muon flux is related to the temperature. This research checks the agreement among different high energy hadronic interactions models and the physical expected behavior of the atmosphere temperature effect by analysing a set of variables, such as the height of the primary interaction and the difference in the muon flux.

The atmospheric temperature effect in the muon flux

- The change in the surface muon intensity can be written as

$$\Delta I_\mu = \int_0^\infty W(X)\Delta T(X)dX \qquad (1)$$

- A temperature coefficient is defined by

$$\alpha(X) = \frac{T(X)}{I_\mu^0}W(X) \qquad (2)$$

- Despite the fact that temperature and pressure depend on the altitude, an isothermal approximation can be done:

$$T_{eff} = \frac{\int_0^\infty W(X)T(X)dX}{\int_0^\infty W(X)dX} = \frac{\int_0^\infty I_\mu^0\alpha(X)dX}{\int_0^\infty W(X)dX} \qquad (3)$$

- An effective temperature can be related with an effective temperature coefficient

$$\alpha_T = \int_0^\infty \alpha(X)dX \qquad (4)$$

- With this definition, the expression (3) is rewritten by the form

$$T_{eff} = \frac{I_\mu^0\alpha_T}{\int_0^\infty W(X)dX} \qquad (5)$$

- Equation (5) can be related to (1) to infer

$$\frac{\Delta I_\mu}{I_\mu^0} = \alpha_T\frac{\Delta T_{eff}}{\langle T_{eff}\rangle} \qquad (6)$$

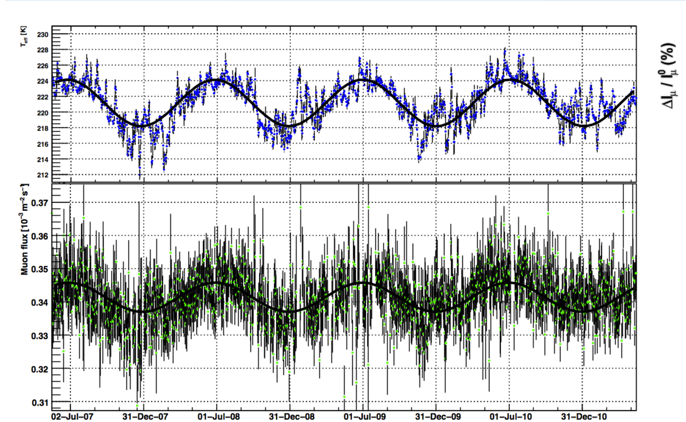
- The change in the surface muon intensity can be seen as the muon flux:

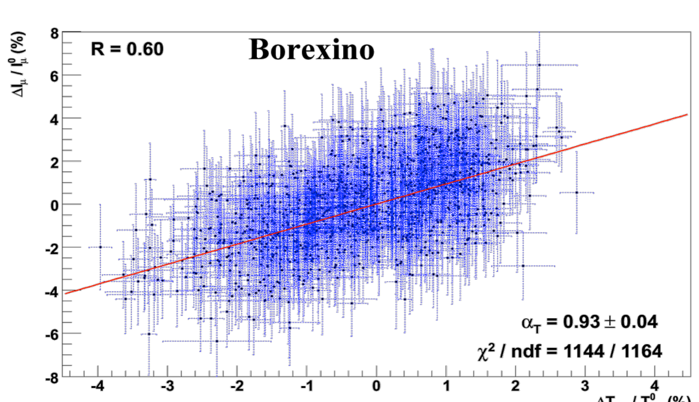
$$\frac{\Delta I_\mu}{I_\mu} = \left[\frac{\Delta N_i/t_i}{\epsilon A_{eff}\Omega}\right] \Big/ \left[\frac{N_i/t_i}{\epsilon A_{eff}\Omega}\right] = \left[\frac{\Delta N_i}{t_i}\right] \Big/ \left[\frac{N_i}{t_i}\right] = \frac{\Delta R_\mu}{\langle R_\mu\rangle} \qquad (7)$$

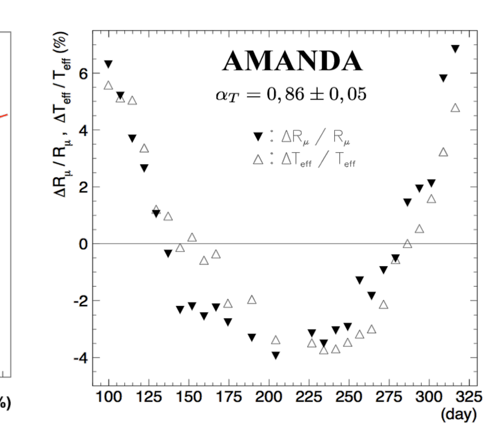
- By using equations (6) and (7):

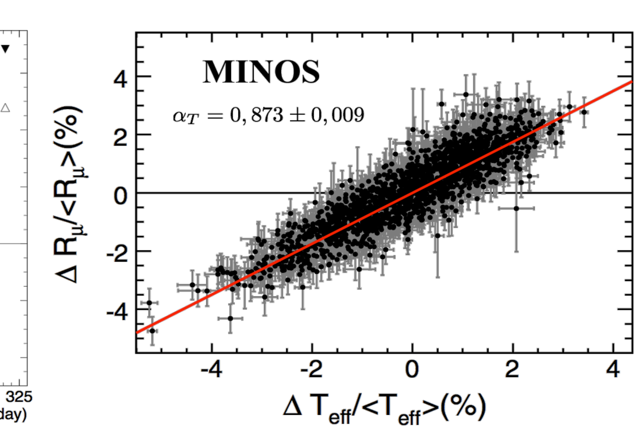
$$\frac{\Delta R_\mu}{\langle R_\mu\rangle} = \alpha_T\frac{\Delta T_{eff}}{\langle T_{eff}\rangle}$$

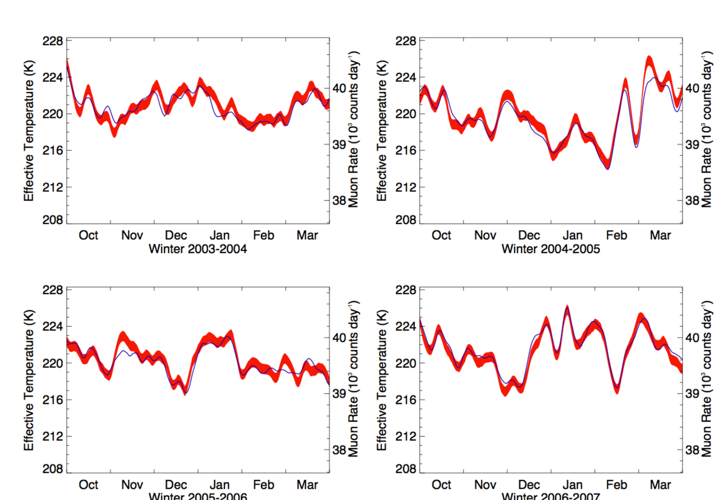
[1] Bouchta, A. **Seasonal variation of the muon flux seen by AMANDA**. 26th ICRC (1999).
[2] Bellini, G. *et al.* **Cosmic-muon flux and annual modulation in Borexino at 3800 mwe depth**. arXiv: 1202.6403 (2012)
[3] Ambrosio, M. *et al.* **Seasonal variation in the underground muon intensity as seen by MACRO**. Astropart. Phys. 7. (1997)
[4] Adamson, P. *et al.* **Observation of muon intensity variations by season with the MINOS far detector**. Phys. Rev. D81. (2010)
[5] Osprey, S. *et al.* **Sudden stratospheric warmings seen in MINOS deep un- derground muon data**. Geophysical Research Letters, vol. 36, L05809. (2009)

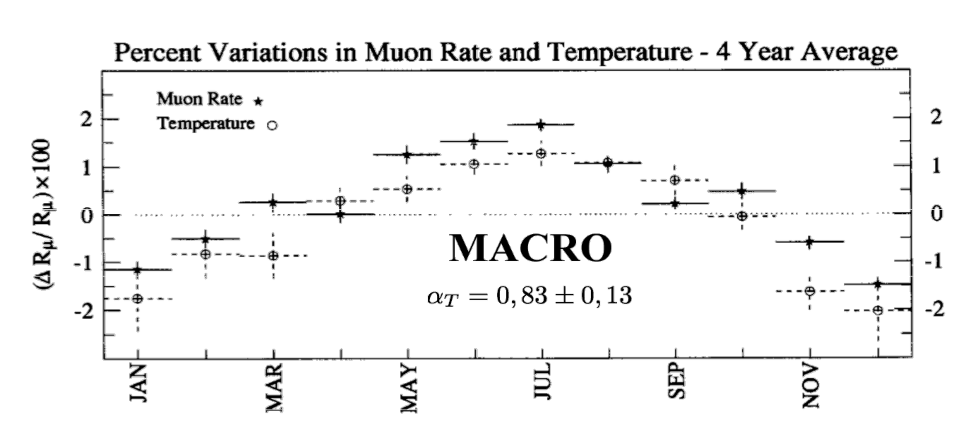


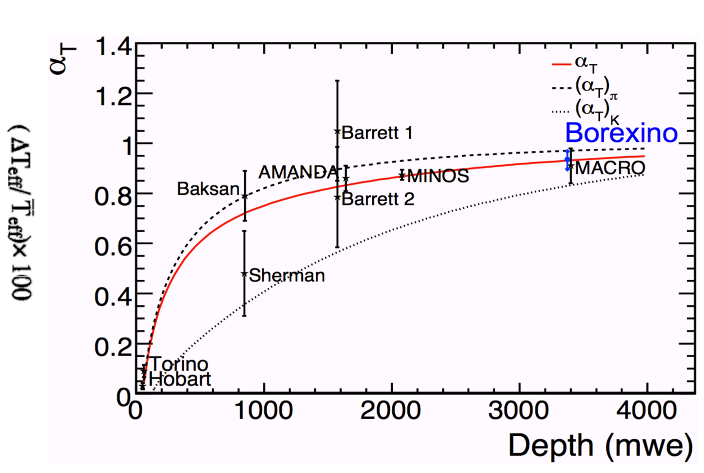












The atmospheric model

- 78.1% N_2; 21.0% O_2; 0.9% Ar
- 5 layers, all parallel to the ground
- The first 4 layers are exponential

$$X(h)_i = a_i + b_i e^{-\frac{h}{c_i}}$$

- The last and highest one is linear

$$X(h)_5 = a_5 - b_5\frac{h}{c_5}$$

- The parameters a_i, b_i and c_i are defined experimentally
- The interfaces of the layers must be continuous

$$X(h_i)_i = X(h_i)_{i+1}; \quad \left.\frac{dX_i}{dh}\right|_{h_i} = \left.\frac{dX_{i+1}}{dh}\right|_{h_i}$$

- $X(h) = 0$ for $h = 112.8$ km

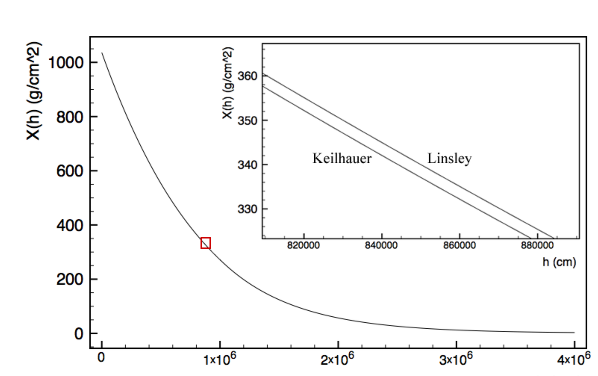
The U.S. parameterizations

- Linsley [Private communications by M. Hillas (1988)]

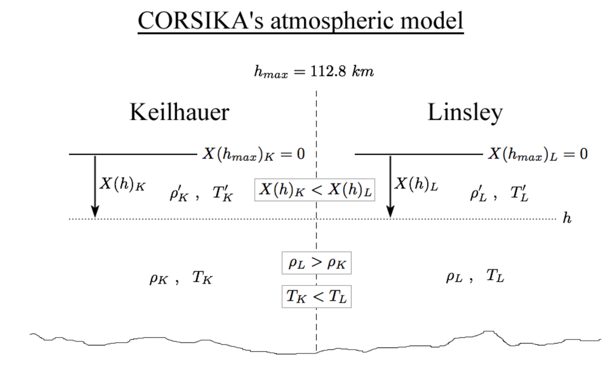
Layer	Altitude (km)	a_i (g/cm²)	b_i (g/cm²)	c_i (cm)
1	0 – 4	– 186.5562	1222.6562	994186.38
2	4 – 10	– 94.919	1144.9069	878153.55
3	10 – 40	0.61289	1305.5948	636143.04
4	40 – 100	–	540.1778	772170.16
5	> 100	0.01128292	1	10^9

- Keilhauer [Astropart. Phys. 22, p. 249. (2004)]

Layer	Altitude (km)	a_i (g/cm²)	b_i (g/cm²)	c_i (cm)
1	0 – 7.0	– 149.801663	1183.6071	954248.34
2	7 – 11.4	– 57.932486	1144.0425	800005.34
3	11.4 – 37.0	0.63631894	1322.9748	629568.93
4	37.0 – 100.0	$4.35453690.10^{-4}$	655.67307	737521.77
5	> 100.0	0.01128292	1	10^9



CORSIKA's atmospheric model



The research goals

- Find the relation parameter α_X between a variation in the muon flux and a variation in the atmospheric parametrization used in the CORSIKA package for EAS simulation.
  - **Co**smic **R**ay **Si**mulation for **KA**SCADE
  - MC modular code for simulating EAS

$$\frac{R_\mu^L - R_\mu^K}{R_\mu^K} = \alpha_X\frac{X_L - X_K}{X_K} \quad \Rightarrow \quad \frac{\Delta R_\mu}{\langle R_\mu\rangle} = \alpha_X\frac{\Delta X}{X}$$

- Verify if the simulation is in agreement with all physical expected behaviors for:
  - Different primary compositions
  - Different hadronic interaction models:
    - QGSJET 01C
    - QGSJETII.3
    - SIBYLL 2.1

Parameters used in the simulations

Composition	Parametrization	# of EAS (×10⁶)	Energy (TeV)	Zenith	Azimuth
H	Linsley, Keilhauer	1 (01), 1 (II), 1 (S)	100	0° – 70°	free
He	Linsley, Keilhauer	1 (01), 1 (II), 1 (S)	100	0° – 70°	free
Fe	Linsley, Keilhauer	1 (01), 1 (II), 1 (S)	100	0° – 70°	free

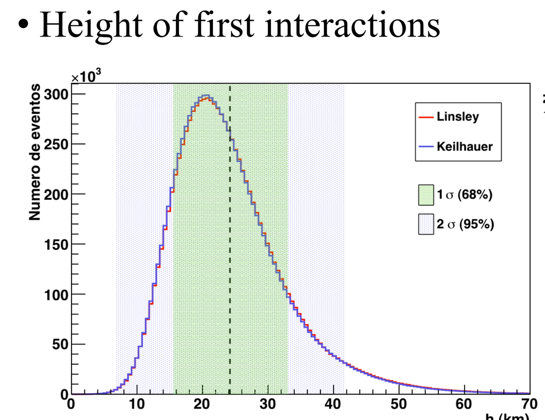
- Particles with less than 85 GeV are not followed by the simulation

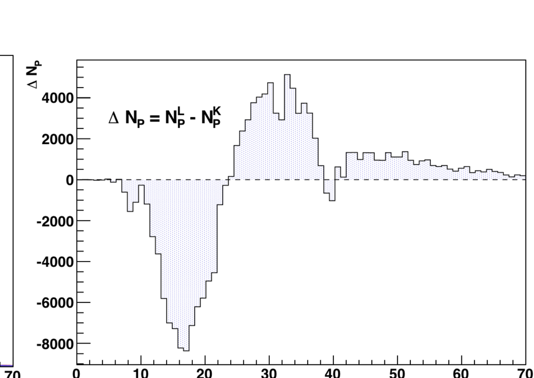
Expected results

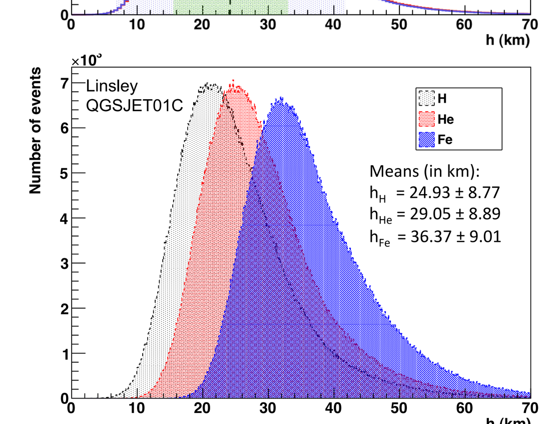
- Linsley has a lower density profile for the EAS, thus
  - Higher mean value of the altitude of first interaction for Linsley
  - Produces more múons than Keilhauer's parameterization
  - $\Delta X/X > 0$ and $\Delta R/R > 0$, resulting in $\alpha_X > 0$
- Altitude of first interaction distribution proportional to A
- Bigger differences in $\Delta X/X$ for higher altitudes
  - Bigger differences in $\Delta R/R$
  - The gap between the mean values of first interactions should increase
- Lower energy muons blinds the atmosphere's temperature effects
  - Higher energy cuts should result in more significant values for ΔR

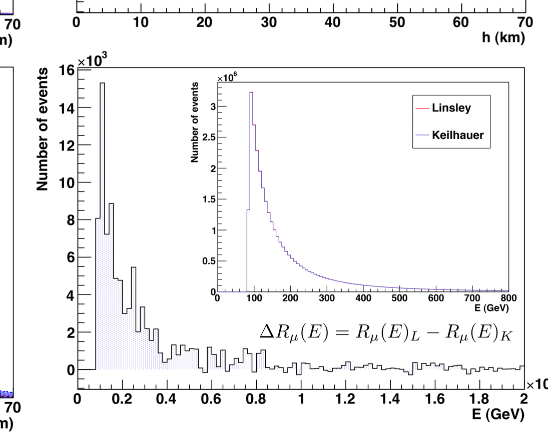
RESULTS

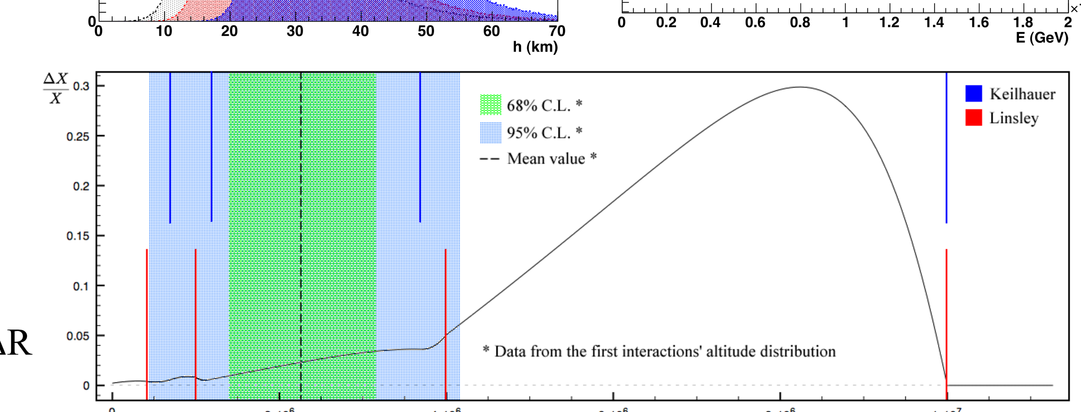
- Height of first interactions











- Only muons with E ≥ 85 GeV are considered

Model	Composition	R_μ (×10³) Linsley	R_μ (×10³) Keilhauer	$\overline{h_L}$ (km)	$\overline{h_K}$ (km)	$\Delta R_\mu/\langle R_\mu\rangle(\times10^{-3})$	$\Delta X/X$	α_X
QGSJET 01C	*H*	(31,749 ± 6)	(30,917 ± 6)	25.0 ± 8.9	24.8 ± 8.8	3.0 ± 0.2	$0.026^{+0.009}_{-0.013}$	$0.11^{+0.04}_{-0.06}$
	He	(42,907 ± 6)	(42,777 ± 6)	29.2 ± 9.2	28.9 ± 9.0	3.0 ± 0.2	$0.031^{+0.004}_{-0.013}$	$0.09^{+0.01}_{-0.04}$
	Fe	(53,546 ± 7)	(53,375 ± 7)	36.7 ± 9.7	36.3 ± 9.4	3.2 ± 0.2	$0.036^{+0.014}_{-0.007}$	$0.09^{+0.03}_{-0.02}$
QGSJETII.3	*H*	(31,002 ± 6)	(30,916 ± 6)	25.0 ± 9.0	24.8 ± 8.8	2.7 ± 0.3	$0.026^{+0.009}_{-0.013}$	$0.10^{+0.04}_{-0.05}$
	He	(42,298 ± 6)	(42,174 ± 6)	29.2 ± 9.2	29.1 ± 9.0	2.9 ± 0.2	$0.031^{+0.004}_{-0.013}$	$0.09^{+0.01}_{-0.04}$
	Fe	(56,999 ± 7)	(56,812 ± 7)	36.6 ± 9.7	36.1 ± 9.4	3.3 ± 0.2	$0.036^{+0.014}_{-0.007}$	$0.09^{+0.03}_{-0.02}$
SIBYLL 2.1	*H*	(31,152 ± 7)	(31,053 ± 7)	25.1 ± 9.0	24.8 ± 8.8	3.2 ± 0.3	$0.026^{+0.009}_{-0.013}$	$0.12^{+0.04}_{-0.01}$
	He	(41,800 ± 6)	(41,661 ± 6)	28.6 ± 9.2	28.3 ± 9.0	3.3 ± 0.2	$0.031^{+0.005}_{-0.013}$	$0.11^{+0.02}_{-0.04}$
	Fe	(54,837 ± 7)	(54,666 ± 7)	36.6 ± 9.7	36.2 ± 9.4	3.1 ± 0.2	$0.036^{+0.014}_{-0.007}$	$0.09^{+0.03}_{-0.02}$

- Only muons with E ≥ 600 GeV are considered

Model	Composition	R_μ (×10³) Linsley	R_μ (×10³) Keilhauer	$\overline{h_L}$ (km)	$\overline{h_K}$ (km)	$\Delta R_\mu/\langle R_\mu\rangle(\times10^{-3})$	$\Delta X/X$	α_X
QGSJET 01C	*H*	(1,922 ± 1)	(1,909 ± 1)	25.0 ± 8.9	24.8 ± 8.8	7.2 ± 1.0	$0.026^{+0.009}_{-0.013}$	$0.27^{+0.10}_{-0.14}$
	He	(2,431 ± 1)	(2,412 ± 1)	29.2 ± 9.2	28.9 ± 9.0	8.1 ± 0.9	$0.031^{+0.004}_{-0.013}$	$0.25^{+0.04}_{-0.10}$
	Fe	(184 ± 0.4)	(182 ± 0.4)	36.7 ± 9.7	36.3 ± 9.4	11.6 ± 3.3	$0.036^{+0.014}_{-0.007}$	$0.32^{+0.15}_{-0.11}$
QGSJETII.3	*H*	(1,913 ± 1)	(1,902 ± 1)	25.0 ± 9.0	24.8 ± 8.8	5.9 ± 1.0	$0.026^{+0.009}_{-0.013}$	$0.22^{+0.08}_{-0.12}$
	He	(2,461 ± 1)	(2,441 ± 1)	29.2 ± 9.2	29.1 ± 9.0	8.1 ± 0.9	$0.031^{+0.004}_{-0.013}$	$0.26^{+0.04}_{-0.10}$
	Fe	(295 ± 0.5)	(292 ± 0.5)	36.6 ± 9.7	36.1 ± 9.4	9.3 ± 2.6	$0.036^{+0.014}_{-0.007}$	$0.26^{+0.12}_{-0.09}$
SIBYLL 2.1	*H*	(1,926 ± 1)	(1,915 ± 1)	25.1 ± 9.0	24.8 ± 8.8	5.3 ± 1.0	$0.026^{+0.009}_{-0.013}$	$0.20^{+0.08}_{-0.11}$
	He	(2,394 ± 1)	(2,379 ± 6)	28.6 ± 9.2	28.3 ± 9.0	6.0 ± 0.9	$0.031^{+0.005}_{-0.013}$	$0.19^{+0.04}_{-0.09}$
	Fe	(466 ± 0.7)	(462 ± 0.7)	36.6 ± 9.7	36.2 ± 9.4	9.7 ± 2.1	$0.036^{+0.014}_{-0.007}$	$0.27^{+0.12}_{-0.08}$

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